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Multisensor Data Fusion
for the Vessel Traffic System

by

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ABSTRACT

This report describes the development of an algorithm to fuse redundant observations due to multiple sensor coverage of a vessel within the United States Coast Guards(USCG) Vessel Traffic Services(VTS) system. Fuzzy membership functions are used as a measure of correlation, and a fuzzy associative system determines which observations represent the same vessel. The result is a computationally efficient algorithm. The output of the system is a unique set of vessels identified by unique platform identifiers. Results of tests based on computer simulation of overlapping radar coverage show that the fusion algorithm correctly correlates and fuses the sensor observations.

I. INTRODUCTION

The United States Coast Guard uses the US Navy's Joint Maritime Command Information System (JMCIS) software as the core software in their Vessel Traffic Services (VTS) systems. This software allows numerous sensors of various types, primarily radar, to make reports to the central supervisory and controlling site, the Vessel Traffic Center (VTC). At the VTC, the sensor information is plotted as tracks on the displays of the operators who are tasked with monitoring vessel traffic and providing advisories to vessels in transit or anchoring in key waterways. Figure 1 presents an overview of the data flow within the VTS system. Current VTS software lacks a mechanism to correlate duplicate sensor tracks which would reduce the amount of superfluous information presented to each operator. This report proposes a fuzzy association approach to the fusion of this multisensor data.

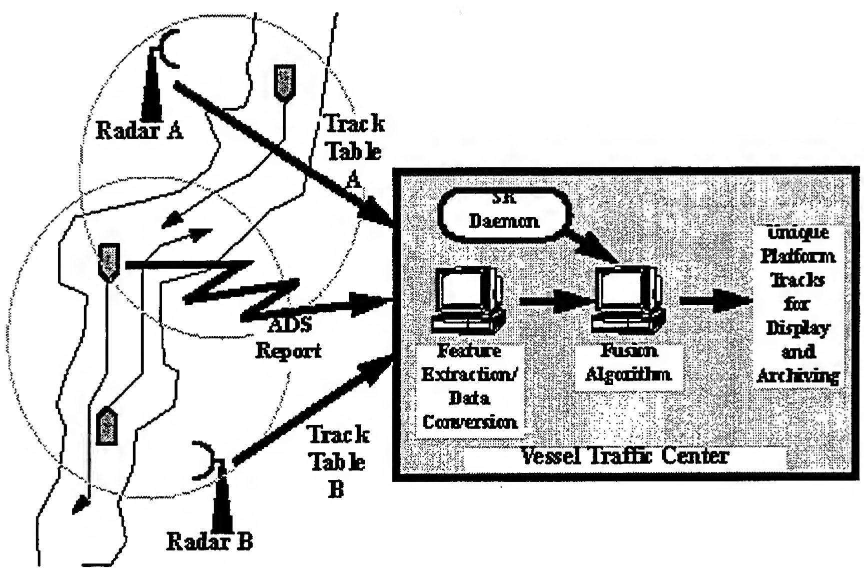


Figure 1

II. APPROACH

The algorithm performs central level fusion on data from various sensor sources providing vessel tracks for display and archival purposes. The algorithm is a refinement of a previously proposed algorithm [1] to fuse the outputs of sensors providing overlapping coverage. The algorithm has been generalized to accept and fuse an arbitrary number of tracks from any available sensor that can provide any of the following feature information: latitude, longitude, course,

speed, and size (approximately length times beam). The data collected are fused to create a single unified track table for display to the VTS operators and for maintenance of an historical record. The fusion process consists of several levels in order to achieve an integrated data set. Also, separate data conversion mechanisms are required to prepare the data for fusion but are unimportant to the actual fusion process. Figure 2 provides an overview of the fusion process.

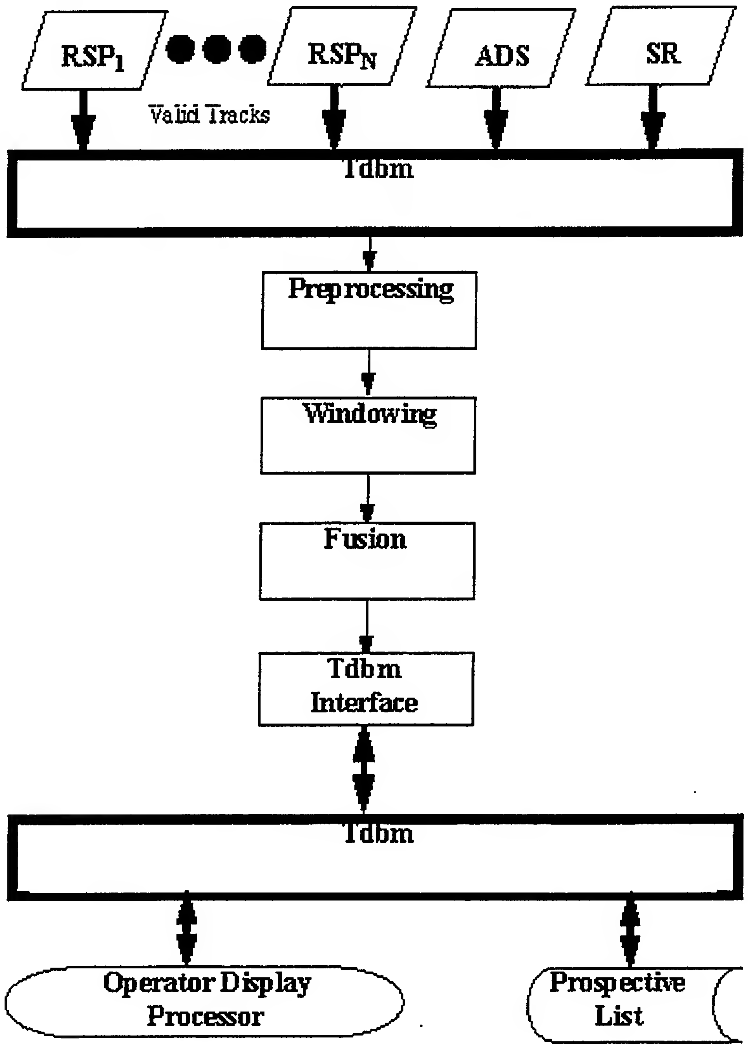


Figure 2 OVERVIEW OF FUSION ALGORITHM

With the relevant features extracted and the most recent sensor observations isolated, the sensor tracks are now ready to be correlated and fused where necessary. Let us first present an overview of fuzzy association as it applies to fusion and then details its application to the VTS problem.

III. FUZZY ASSOCIATION FOR FUSION

The goal of the fusion algorithm is to combine or fuse tracks of the same vessel observed and reported to the system by different input devices whether from radar processors or by some other sensor. These fused tracks can then be associated with a unique platform identifier represented in the system by a unique platform number and a unique platform icon. The fuzzy membership is used to achieve this fusion. The membership function from fuzzy set theory provides a mechanism to measure correlation between observation or track pairs.

Data fusion is a process dealing with association, correlation and combination of data from multiple sources to achieve a refined position and identity estimation [2]. The aim of the data fusion is to derive more information in the final result than is present in only a single source of information. The combination of multiple sensors has the added benefit of redundancy of reporting. The failure of a single sensor then becomes non critical for coverage of an area. In addition, multiple sensors provide improved spatial coverage of an area with improved resolution over that offered by a single sensor.

Data fusion is usually classified into three types: positional fusion, identity fusion and threat assessment [3]. Positional fusion endeavors to determine an improved position estimate of a target by combining parametric data, such as azimuth, range, and range rate. Identity fusion uses known characteristics to determine the identity of a target. Threat assessment is the highest level of data fusion and is used for military or intelligence fusion systems to determine the meaning of the fused data from an adversarial point of view. The application of data fusion to JMCIS and VTS requires only positional fusion, and the method by which this is achieved will now be discussed.

IV. POSITIONAL FUSION

Initial positional fusion is accomplished by the Adaptive Kalman filter tracker operating at each remote radar site. This is considered sensor level fusion. The proposed algorithm assumes that the sensor level fusion is being performed correctly and that valid tracks are being generated and sent to the central site for further processing. Central level positional fusion is performed at the central site with the aim of eliminating the redundancies in observations or tracks being generated by each of the sensor level fusion algorithms. These redundancies occur when there is overlapping coverage provided by sensors(i.e. two radars that cover the same waterway). Each radar gets returns on the target, starts a track and forwards the track information to the central site for display and historical record keeping.

Additional redundant observations can result from the input of tracks from the Automated Dependent Surveillance (ADS) system [4] or generated estimated

positions (EPs) for vessels based on Standard Routes (SRs) generated by the Predictive Decision Support Aids (PDSA) [5]. Each of these vessel observations appear in the Tdbm database [6] along with a date/time stamp. Each of these sources of track information include sufficient information to generate the following attributes: position (latitude and longitude), course, speed and size.

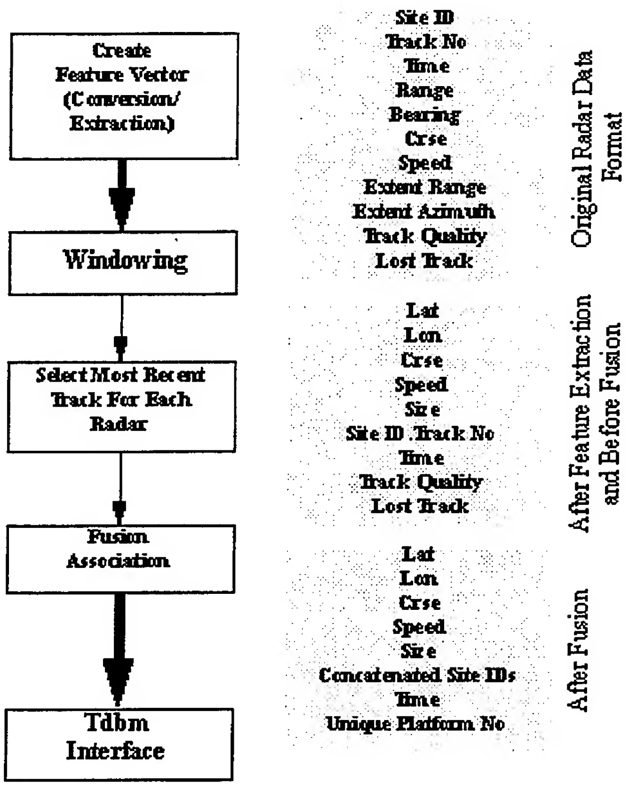


Figure 3 FUSION ALGORITHM FLOW

The fuzzy association system takes these attributes and makes membership or similarity by correlation. This is accomplished as follows. Fuzzy set theory considers the partial membership of an object in a set. A membership function, used to grade the elements of a set in the range [0,1]. The grade of membership of the correlation of an object to a defined set. The closer the object is graded to one, the higher the membership of the object is in the set and the more compatible with the set being considered.

Design of a fuzzy association system involves the following four steps: determining the universe of discourse of inputs and outputs; designing membership functions; choosing fuzzy rules to relate the inputs and outputs; and determining a defuzzifying technique.

When comparing the latitudes of two separate radar tracks to see if they are similar a geometric membership can be constructed that takes into account the errors present in the system inherent to each remote site generating a track. A triangular shaped membership function as in Figure 4 is a good choice for a

positional comparison because of the accuracy of the radars in reporting the target position.

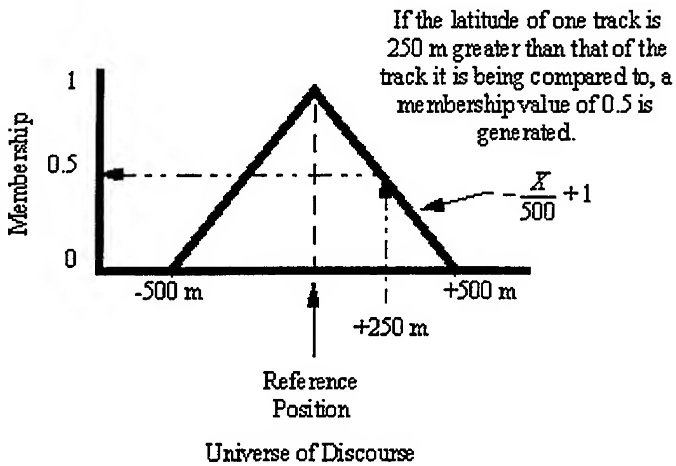


Figure 4 POSITION(LAT/LONG) MEMBERSHIP FUNCTION

In the example, the latitude given in one track is subtracted from the latitude given in another track held as the reference. The difference in latitude is used to determine the membership value. Figure 5 shows the membership functions used in the algorithm.

In general, the design of membership functions is based on the attributes inherent to those aspects being compared. Since both radar and ADS positions reported to the system are relatively accurate, the triangular membership function is appropriate. For other attributes where there is less accuracy such as in speed or size, broadening the roof of the membership function to include a greater range of values is valuable. It is also useful to truncate the membership function at a given value as in the case of the Course Membership Function creating a trapezoidal shape to allow a generous association within a reasonable range of values but not outside of a fixed range.

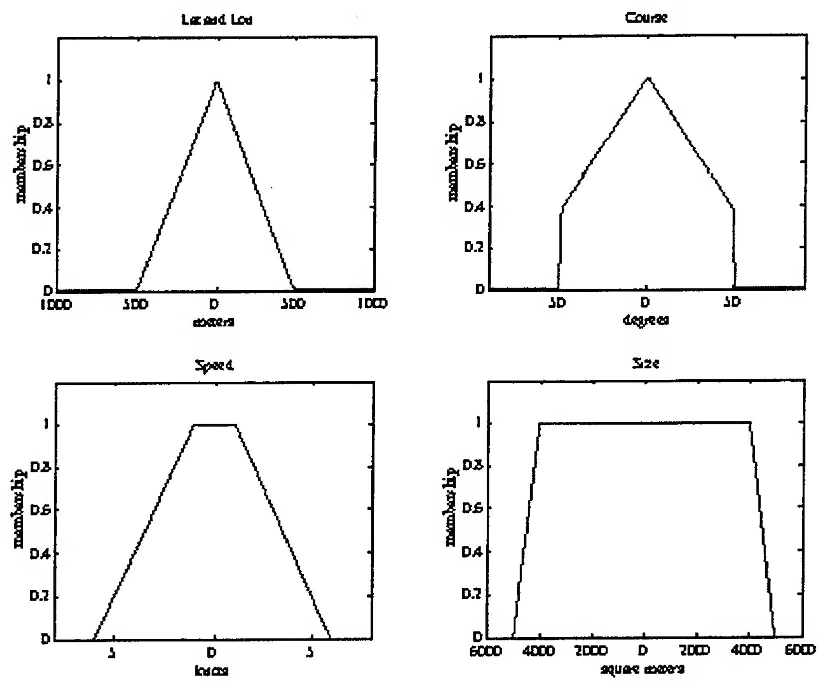


Figure 5 MEMBERSHIP FUNCTIONS USED IN FUZZY ASSOCIATIVE SYSTEM

Next, in order to evaluate each of the membership values returned, a threshold needs to be established that reflects the physical limitations. In the case of the radar returns, a variable threshold is set that takes into account accuracy limitations of the radar dependent on the range of the target. Figure 6 graphically depicts the variable threshold employed in the simulation.

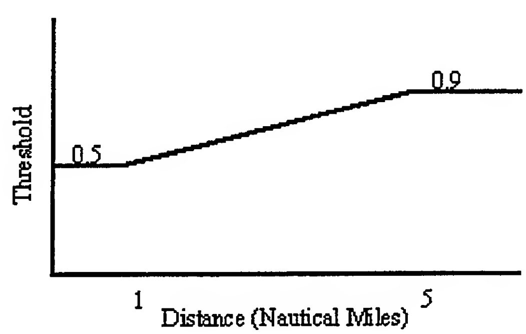


Figure 6 VARIABLE THRESHOLD FUNCTIONS

Once all of the attributes for the track pair being assessed have been assigned membership values, they can be checked to see that they exceed the designated threshold. Each value is checked sequentially starting with latitude to ensure that it exceeds the threshold. If it does not, no further checks are made and association fails. This method has the advantage of computational efficiency. If all values exceed the assigned threshold, association is made as indicated by a binary output of '1' from the defuzzifier.

Figure 7 schematically shows the action of the fuzzy associative system. If the membership values, θ_i, all exceed the single threshold, ϕ, the two tracks would be associated. If the ϕ exceeds any of the θ_i, no association would be made.

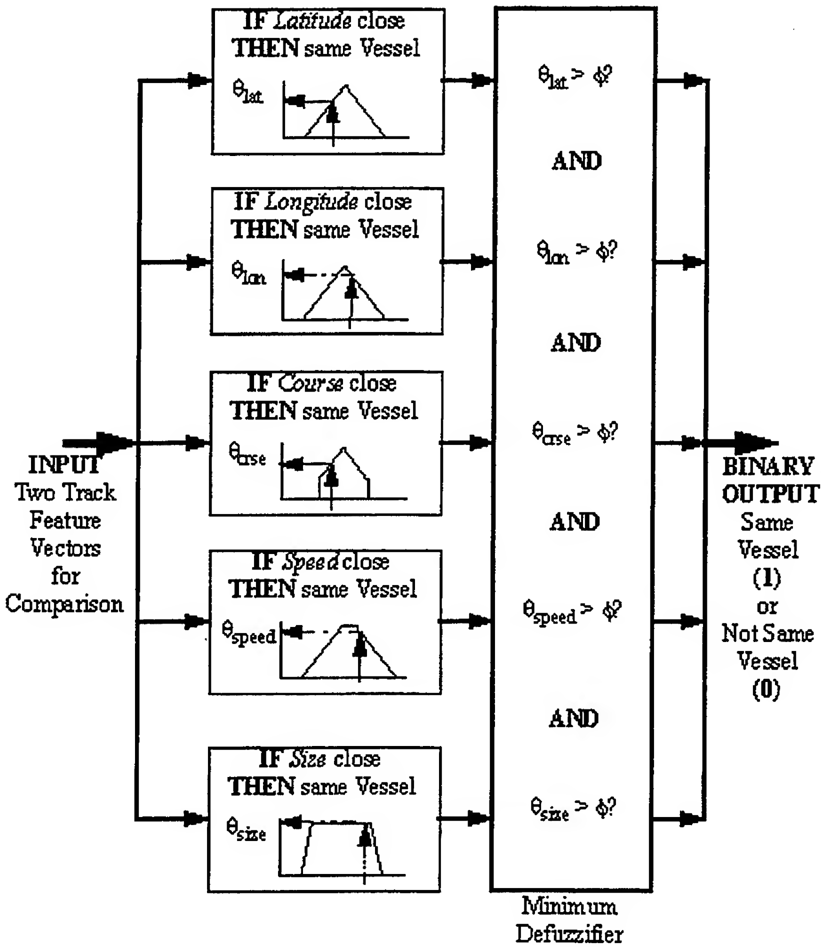


Figure 7 FUZZY ASSOCIATIVE SYSTEM

The result is a single unified set of tracks representing a unique set of vessels present in the system in that time window. In the fused tracks, the original reporting sensor and its assigned track number are maintained for archival purposes as well as to assist in maintaining a unique platform number.

V. DATABASE FUSION

The data set is now ready to be used to update the Tdbm. The site and track number field is used to determine if this track being added is new to the system. If the search of the site and track number field in the Tdbm is successful, the associated platform number is appended to the track in question. If the search fails, a new platform track number is generated and the operator can be alerted to the new "unknown" track.

At this point the multilevel sensor fusion cycle is complete. The output of the various sensors have been related to each other, and the unified set has been related to the previous sets (the Tdbm). The data window can now be moved forward in time to gather in the next batch of sensor tracks and the process repeated. The next section will describe the simulation used to test the algorithm.

VI. RESULTS

A simulation was created to provide sensor tracks similar to the link tracks available in the Tdbm for the fusion algorithm to operate on. The area chosen for this simulation was the Upper Bay of New York Harbor whereby the Governor's Island and Bank Street radars provide overlapping coverage as depicted in Figure 8.

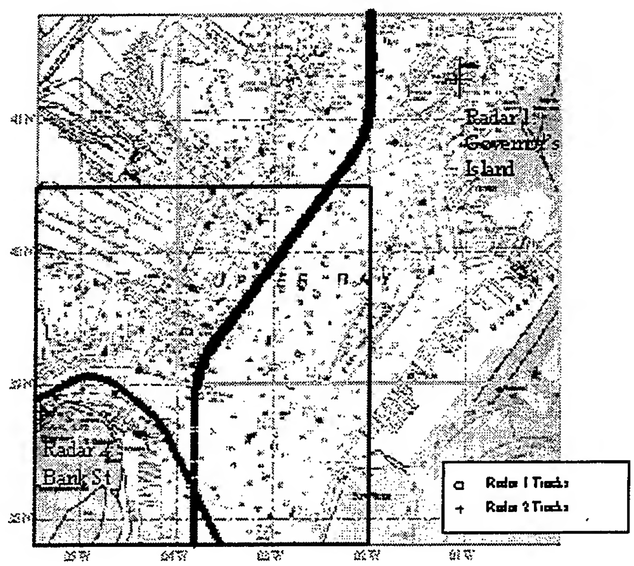


Figure 8 ESTIMATED TRACKS FOR VESSELS A & B

Simulation Construction

A Simulink© simulation module was created to model vessel traffic transiting this area. Figure 8 through Figure 11 depict the estimated tracks produced. Vessels were modeled with a speed of 10 knots and a turn rate of 45 degrees in three minutes. The simulation used Runge-Kutte 45 integration to compute the smoothed trajectory. The vessel position in terms of latitude and longitude was recorded at three second intervals of simulation time. This time interval reflected the actual expected radar update rate of track reporting to the VTC.

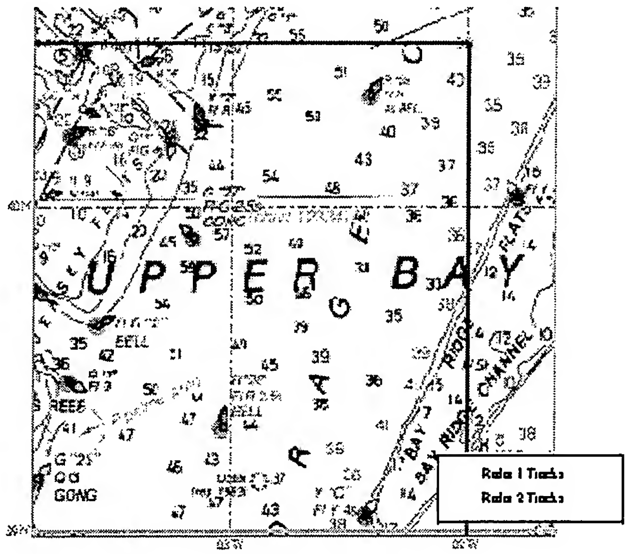


Figure 9 MAGNIFIED VIEW OF VESSELS A & B

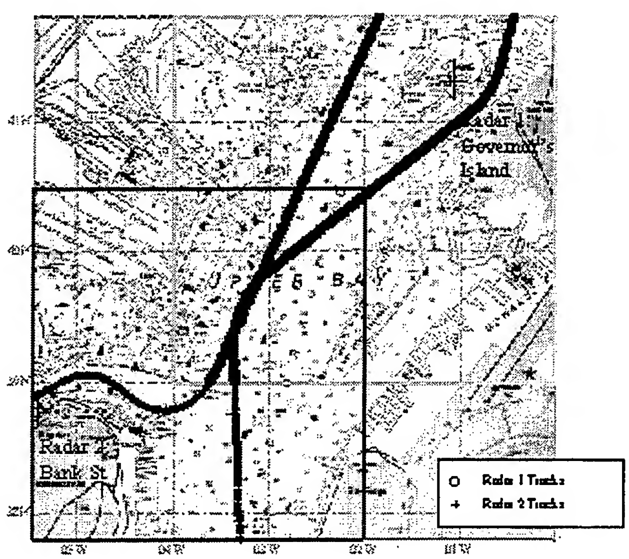


Figure 10 ESTIMATED TRACKS FOR VESSELS C & D

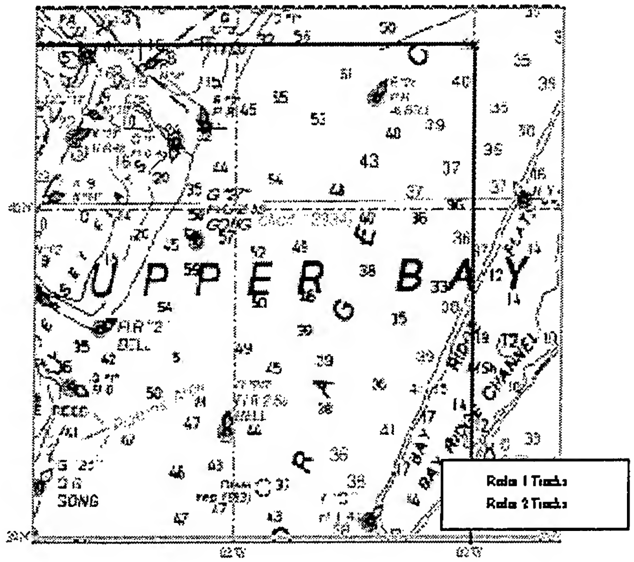


Figure 11 MAGNIFIED VIEW OF VESSELS C & D

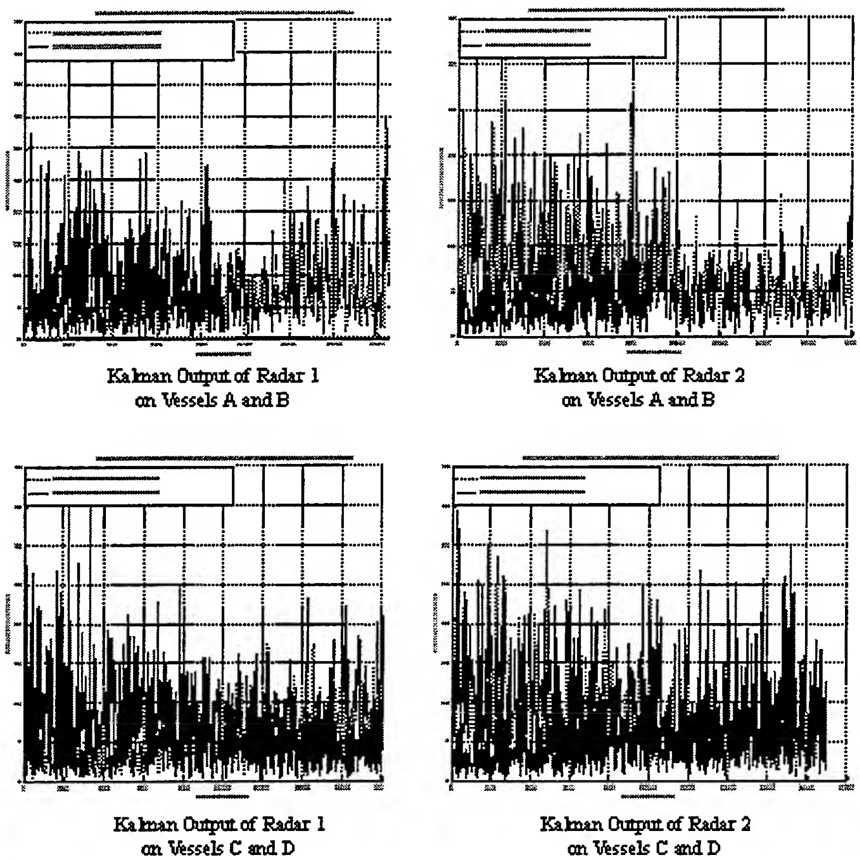
Four separate vessel tracks were generated and processed by a Multitarget Kalman filter[7]. Before being processed by the filter, noise was added to the measurements by converting them to spherical coordinates and adding appropriate range and bearing variance to each set of measurements [8]. The noise was modeled as follows: range variance was based on 7 meter range bins and a uniform distribution; bearing variance was based on taking 50 percent of the Half Power Beamwidth (HPBW) of the receiving radar and assuming a uniform distribution.

With noise added, each set of measurements was processed by the Kalman Filter. Filtering was performed with a q = 10 for slowly maneuvering targets [9]. Filtering for each data set was performed from the perspective of the radar at Governor's Island Radar (Radar 1 in the simulation) and again from the perspective of Bank Street Radar(Radar 2).

The actual GPS survey locations for these sites were used to calculate measurement associations. The complete data sets were then truncated to provide a region of over-lap only in the box defined by 39°N to 40.5°N and 02°W to 04°W. Although the real overlapping regions of coverage for these two radars is circular from the perspective of each radar, rectangular coverage served the purpose of illustrating where fusion should occur.

The data set at this point contained the variance present in the system for position (latitude and longitude), course and speed. The positional noise for each track can be seen in Figure 12 where the miss distances from the actual vessel trajectory are plotted. Course and speed were calculated using the mean of a three point moving average over one minute of simulation time. Figure 13 and

Figure 14 show the output of the filter calculations for course and speed at each point. The boxes with the track numbers indicate the portions of the data set that were kept after truncating for geographic coverage.



Kalman Output of Radar 1 on Vessels A and B

Kalman Output of Radar 2 on Vessels A and B

Kalman Output of Radar 1 on Vessels C and D

Kalman Output of Radar 2 on Vessels C and D

Figure 12 MISS DISTANCES FROM ACTUAL TRACK

In order to model the variance typical in the size feature as reported by radar processors, a statistical analysis was conducted on the limited data set provided by EECEN. Size was a difficult parameter to accurately model because of its dependence on not only the aspect of the vessel presented and the distance of the vessel from the reporting radar, but also the variance in range and bearing variance of the observing radar. From the analysis, it was determined that to achieve roughly the same distribution, the size could be modeled with a normal distribution out to one standard deviation below an arbitrary mean size and two standard deviations above. The size feature was randomized accordingly. Figure 15 shows the histograms of the size features used for each vessel.

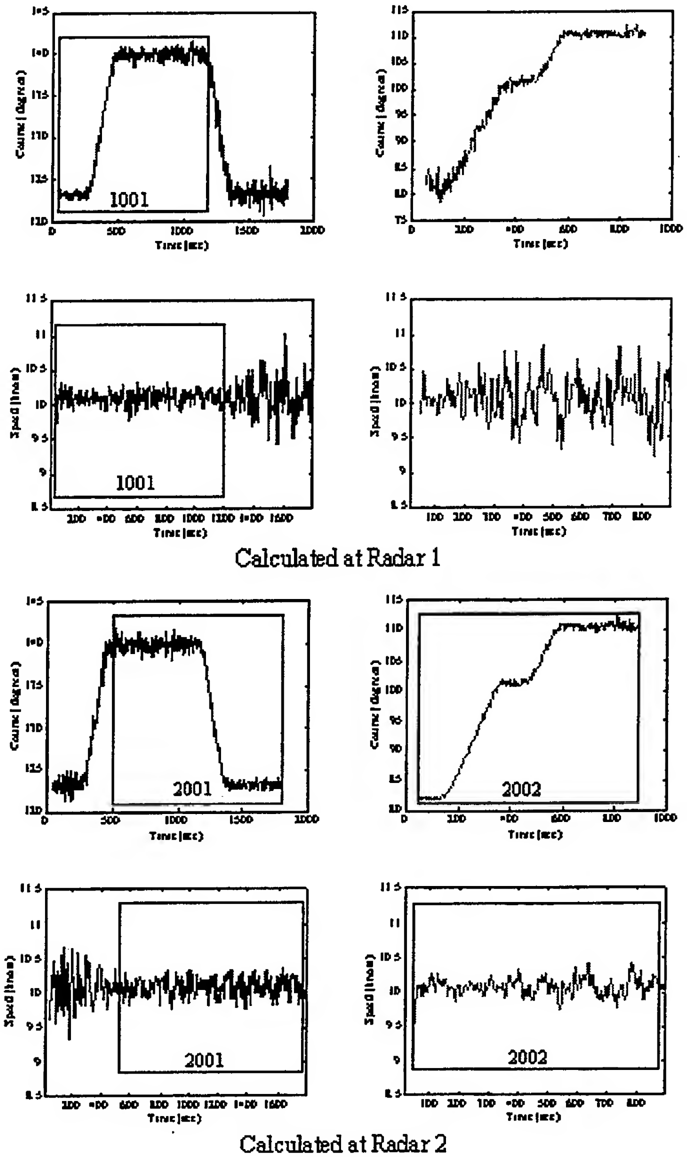
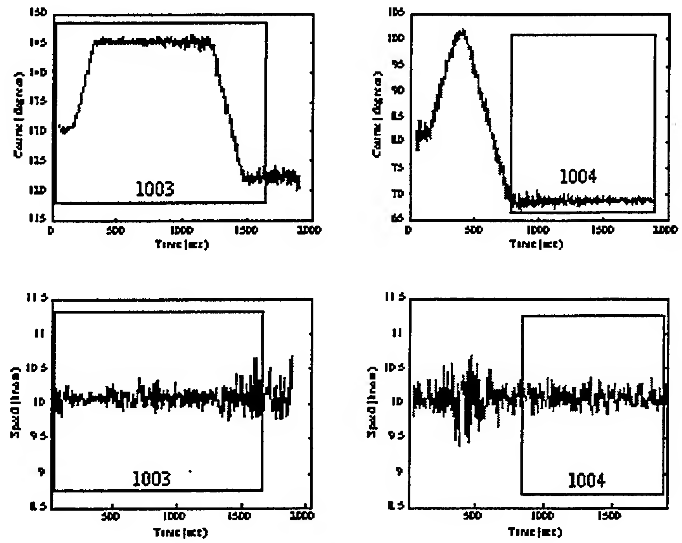
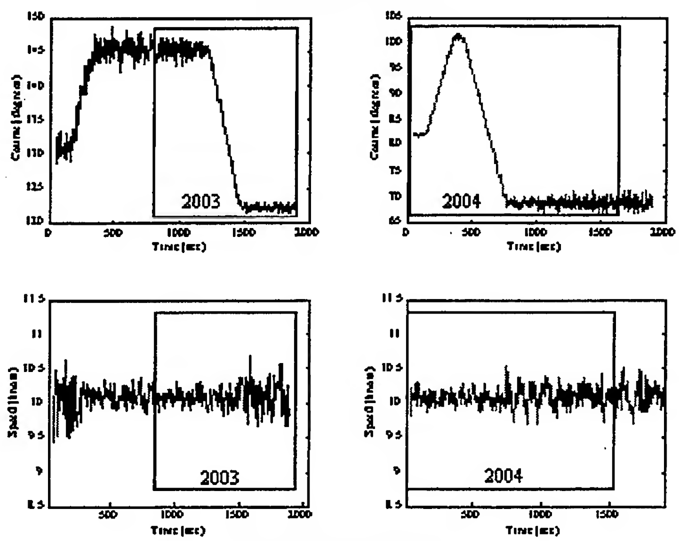


Figure 13 CALCULATED COURSE AND SPEED FOR A & B

The resulting tracks were then combined into one unified track table representing sensor tracks in the Tdbm. Figure 16 shows the plots of each of the tracks. The fusion algorithm was then fed tracks as determined by a sliding 15 second time window moving at three second increments. An animation was generated to monitor the progress of the fusion algorithm. Figure 17 and Figure 19 show snapshots of the output of the algorithm plotted at every fifth (15 second) point. Where fused tracks have been plotted, the originating sites and tracks numbers are shown concatenated together.



Calculated at Radar 1



Calculated at Radar 2

Figure 14 CALCULATED COURSE AND SPEED OF C & D

The output of the algorithm was appended to the Tdbm at each iteration. Independent redundant databases of tracks fused and tracks not fused were generated to simplify performance analysis of the algorithm.

In summary, the algorithm performed correctly under all test scenarios. The test scenarios were as follows.

- Vessels moving in and out of the overlapping cover area (Figure 17 and Figure 18).
- Vessels crossing within multiple coverage area with closest point of approach of 100 meters.
- Two vessels of differing deterministic size with the same location, course and speed.

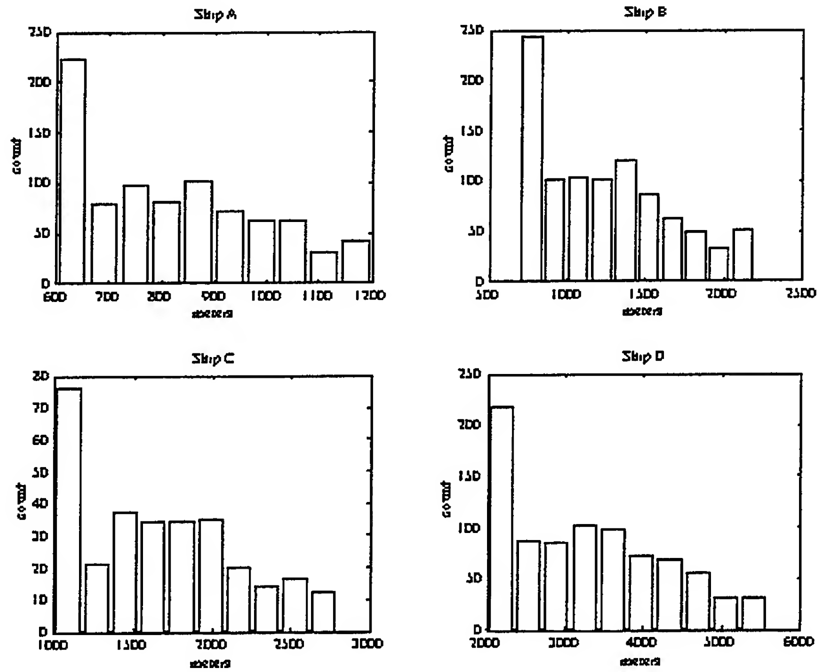
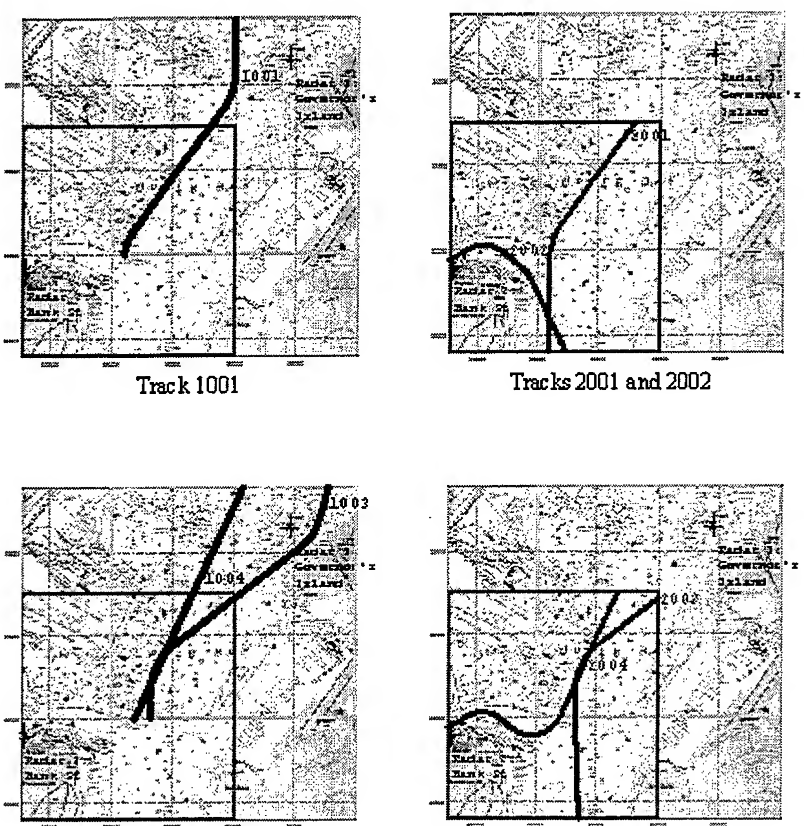


Figure 15 SIZE FEATURE HISTOGRAMS



Track 1001

Tracks 2001 and 2002

Tracks 1003 and 1004

Tracks 2003 and 2004

Figure 16 TRACK INPUT TO FUSION ALGORITHM

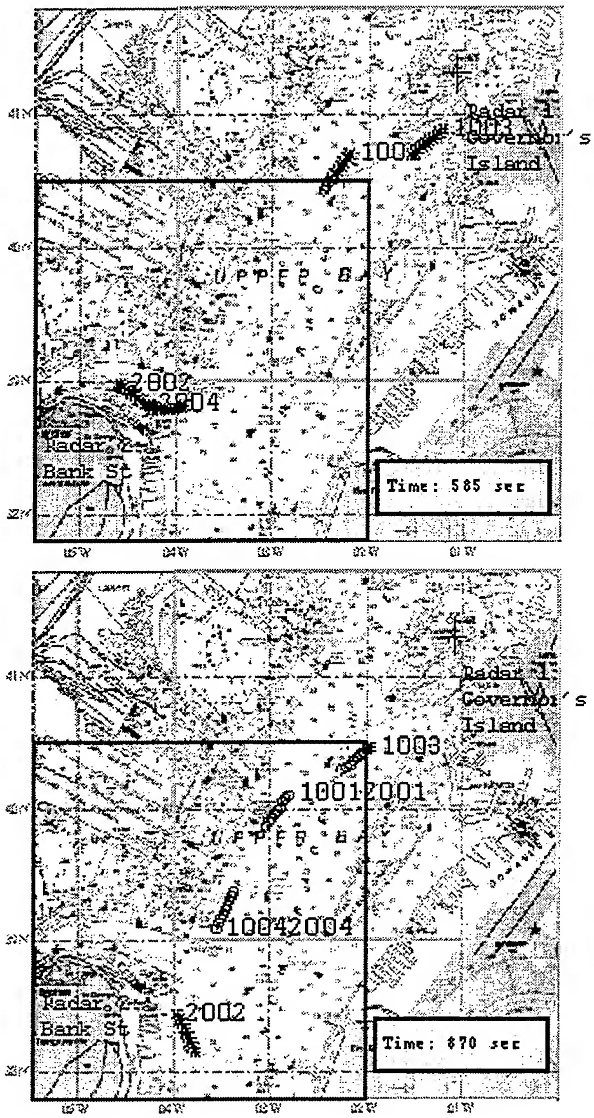


Figure 17 OUTPUT AT TIME 585 & 870

Plots of the resulting fused and not-fused tracks are presented in Figure 19 and, in a magnified view of the overlapping region in Figure 20. The following results were observed: The algorithm correctly fused all tracks within overlap region; the fusion algorithm was able to discriminate vessels with identical position, course and speed but of different size when the size feature was deterministic; the algorithm was also able to correctly fuse tracks with similar features within single coverage areas.

One of the key observations was the effect of the design of the individual membership functions. If the range of the membership function was not sufficiently broad, particularly in the case of the stochastic size parameter, the decision to fuse two tracks was not made.

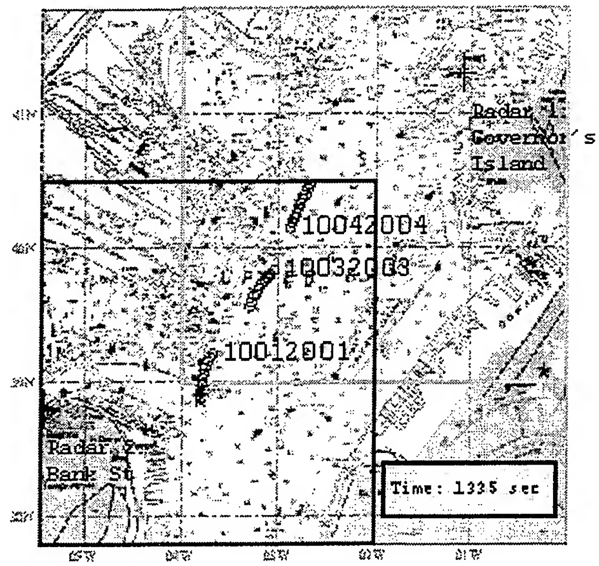


Figure 18 OUTPUT AT TIME 1335

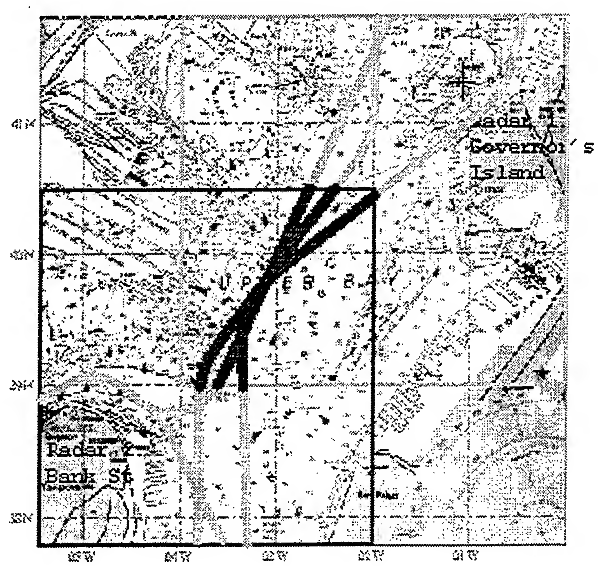


Figure 19 POST FUSION: FUSED(MAGENTA) AND NOT FUSED(CYAN) TRACKS

Overall, the algorithm correctly identified unique tracks and associated a unique platform number with them which remained consistently associated as the vessel transited through multiple coverage areas. The algorithm did fuse N tracks correctly where 2N duplicate tracks were present in the system. Figure 21 shows the resultant unique platform tracks generated and stored in the Tdbm.

VII. CONCLUSIONS

The algorithm performed as expected, fusing tracks that represented multiple coverage of single vessels to produce a unified set of platform tracks in the

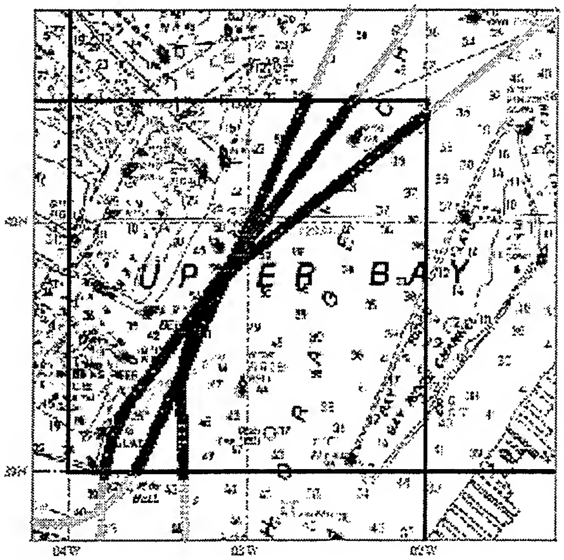


Figure 20 POST FUSION: FUSED TRACKS IN OVERLAP REGION

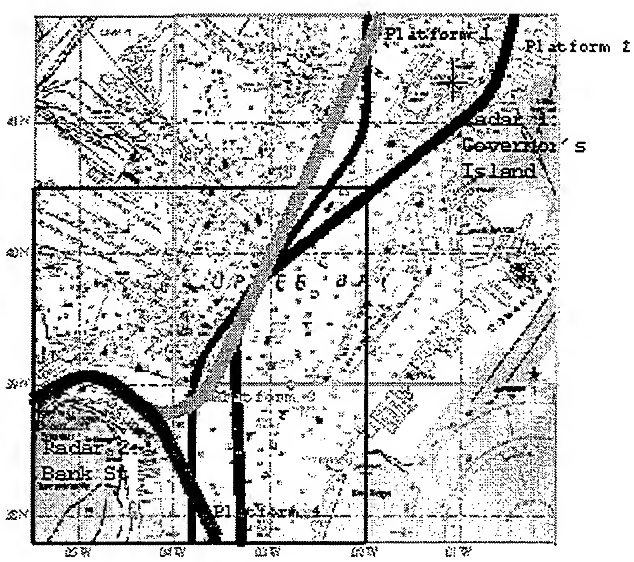


Figure 21 POST FUSION: UNIQUE PLATFORM TRACKS FROM Tdbm

Tdbm. This set represents unique vessels reported to the system. Variance in the parameters of each of the features strongly effects the range and shape of each of the membership functions used to determine association. The more accurately known the variance of a specific feature, the more precise the design of the membership function can be. The result is more accurate association of tracks. The fusion algorithm was computationally efficient and could accurately discriminate vessels. The algorithm could also handle an arbitrary number of vessels from an arbitrary number of sensors of arbitrary type as long as they

were capable of providing some of the five features used for fusion. The algorithm can be easily modified to turn off the evaluation of specified features if those features are not present in the reported tracks. The algorithm can also be modified to add additional features.

The algorithm needs to be tested using real data from a variety of sources that are providing redundant information on the same vessel. These sources include radars, GPS, DGPS, acoustic sensor and system generated tracks. This data has been recently obtained, and the algorithm is undergoing modifications and testing at the time of writing this report.

The United States Coast Guard will be able to implement this algorithm at their Vessel Traffic Centers to reduce the workload on both the system and the operators. This will allow operators to focus on the flow of traffic with less distractions resulting in a more safe environment and the retention of a more accurate historical database than is currently possible.

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